Risk aversion, time preference, and the social cost of carbon

Anthoff, D.; Tol, R.S.J.; Yohe, G.W.

published in
Environmental Research Letters
2009

DOI (link to publisher)
10.1088/1748-9326/4/2/024002

document version
Publisher's PDF, also known as Version of record

Risk aversion, time preference, and the social cost of carbon

2009 Environ. Res. Lett. 4 024002

(http://iopscience.iop.org/1748-9326/4/2/024002)

IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS

Environ. Res. Lett. 4 (2009) 024002 (7pp) doi:10.1088/1748-9326/4/2/024002

Risk aversion, time preference, and the social cost of carbon

David Anthoff[1,2], **Richard S J Tol**[1,3,4] **and Gary W Yohe**[5]

[1] Economic and Social Research Institute, Dublin, Republic of Ireland
[2] International Max Planck Research School of Earth System Modelling, Hamburg, Germany
[3] Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands
[4] Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands
[5] Department of Economics, Wesleyan University, Middletown, CT, USA

Received 4 September 2008
Accepted for publication 30 March 2009
Published 17 April 2009
Online at stacks.iop.org/ERL/4/024002

Abstract

The Stern Review reported a social cost of carbon of over \$300/tC, calling for ambitious climate policy. We here conduct a systematic sensitivity analysis of this result on two crucial parameters: the rate of pure time preference, and the rate of risk aversion. We show that the social cost of carbon lies anywhere in between 0 and \$120 000/tC. However, if we restrict these two parameters to matching observed behaviour, an expected social cost of carbon of \$60/tC results. If we correct this estimate for income differences across the world, the social cost of carbon rises to over \$200/tC.

Keywords: economics of climate change, social cost of carbon, risk aversion, rate of pure time preference

S Supplementary data are available from stacks.iop.org/ERL/4/024002

1. Introduction

The social cost of carbon (the SCC) estimates the discounted value of the damage associated with climate change impacts that would be avoided by reducing carbon emissions by one tonne. It is a useful measure for assessing the benefits of climate policy at any point in time. It is generally thought to increase over time, and textbook economics would recommend that carbon emissions be taxed by a price set equal to the SCC. The *Stern Review* [18–20] reported a SCC in excess of \$300/tC in the absence of any climate policy—an estimate that lies well above the upper bound of \$50/tC that was found in an extensive literature survey and meta-analysis [26]. Many analysts have attributed this high estimate to the very low rate of pure time preference adopted by the *Stern* author team [1, 11, 13, 14, 30].

Others [5, 29] have argued that the *Stern Review* also included unusual assumptions about risk aversion. We respond to this observation by exploring the relative sensitivity of the SCC to both the pure rate of time preference *and* the rate of risk aversion. Our results support the hypothesis that the assumed rate of risk aversion is at least as important as the assumed rate of time preference in determining the social cost of carbon even though our analysis reveals an enormous range of estimates. Some are negative (that is, showing social benefits), but our positive estimates span *six* orders of magnitude on the positive side depending on both the pure rate of time preference and a standard measure of risk aversion.

Philosophers would likely confront this range by choosing a particular estimate based on what they deemed to be appropriate reflections of both parameters [3, 4, 12, 15]. This approach was adopted in the *Stern Review*, but here we take a different tact. Instead of imposing our own normative values on the selection of a single SCC estimate, we look at the behaviours of democratically elected governments to infer distributions of the rates of risk aversion and pure time preference that are actually used in practice. We use the resulting probability density to constrain the estimates of the SCC and compute its expected value. Perhaps surprisingly, the *expected* social cost of carbon turns out to be reasonably close to the value reported in the *Stern Review*.

2. Time preference and risk aversion

To be sure, climate change is a long-term problem. This is why the pure rate of time preference is so important. Greenhouse gas emission reduction over the near-term would mitigate future damages, but they would do little to alter the present climate and/or the present rate of change in climate impacts. The costs of emission abatement must therefore be justified by the benefits of avoided impacts in the future. It follows that any statement about the desirability of climate policy necessarily contains a value judgement about the importance of future gains relative to present sacrifices. The discount rate employed in benefit and cost calculations over time can be thought of as the opportunity cost of investment, but it can also be seen as the relative value of consumption over time. The two are equivalent if the economy is in a dynamic equilibrium; and this equivalence means that time preference is not alone in playing a critical role in determining any SCC estimate.

To explain why, we note that people discount future consumption for two reasons. Firstly, they expect to become richer in the future, and so they care less about an additional dollar then than they do about an additional dollar today. Secondly, they are impatient. We also recall the so-called Ramsey discount rate r that was designed to sustain optimal saving over time [16]. It consists of three components:

$$r = \rho + \eta g \qquad (1)$$

where ρ is the rate of pure time preference, g is the growth rate of per capita consumption, and η is the elasticity of marginal utility of consumption.

Both motives of personal discounting can be detected in the Ramsey rule for dynamic optimality by considering the rate at which people would be willing to sacrifice a dollar of current consumption for additional consumption in the future (see the SOM for brief details). The pure rate of time preference is defined implicitly by the marginal rate of substitution between present and future consumption *under the condition that consumption levels in both periods are equal (so that* $g = 0$). In words, the definition of the pure rate of time preference calibrates inter-temporal trading so that individuals who anticipate constant levels of consumption from one period to the next would be willing to sacrifice one dollar of present consumption if he or she would be compensated with $\$(1+\rho)$ of *extra consumption* in the next period. Higher values of ρ therefore reflect higher degrees of impatience because higher compensation would be required to compensate exactly for the loss of \$1 in current consumption.

Consumption levels need not be constant over time, and the second term in equation (1) works the implication of this fact into this trading calculus. While g measures the growth rate of material consumption, ηg reflects the growth rate of happiness measured in terms of underlying personal utility. If consumption were to climb by $g \times 100\%$ from one period to the next, then each future dollar would be worth $g\eta \times 100\%$ less (assuming no impatience so $\rho \equiv 0$). It follows that our individual would consider sacrificing one dollar in current consumption only if he or she could be compensated by an amount equal to $\$(1 + g\eta)$ in the future.

In contemplating welfare-based equivalence of consumption over time, it is now clear that this trading-based accommodation of growing consumption works in exactly the same way as the pure rate of time preference in defining the rate at which the future needs to be discounted. Put another way, if one considered empirical estimates for both ρ and η that range from zero to three[6], then both parameters should play equally important roles in determining the appropriate discount rate. Perhaps because 'impatience' is intuitively clear while the role of the 'elasticity of marginal utility with respect to consumption' is not, the debate over how the SCC could be so high has focused undue attention over ρ almost to the exclusion of η.

This need not be the case; indeed, the utility-based association with the Ramsey discounting rule shows that this should not be the case. Climate change is not only a long-term problem; it is also a very uncertain problem and a problem that differentially affects people with widely different incomes. The rate of pure time preference ρ speaks only to the first characteristic of the climate policy problem—the timescale issue. The elasticity of marginal utility with respect to consumption, the parameter η, speaks to all three characteristics. It is, first of all, a measure of the curvature of the utility function, which maps material consumption to happiness. It indicates precisely the degree to which an additional dollar brings less joy as income increases. Moreover, the parameter η can also be interpreted as a measure of how one evaluates a gain of a dollar for rich person relative to a gain of a dollar for a poor person. This is why η is occasionally referred to as the parameter of inequity aversion. In its simplest form, equity-weighted impacts are based on the following equation

$$D_w = \sum_c \left(\frac{y_w}{y_c}\right)^\eta D_c \qquad (2)$$

where D_w is the globally aggregate impact, D_c is the monetary impact of climate change in country c, y_w is globally average per capita income, and y_c is per capita income in country c. If $\eta = 0$, the global impact is the unweighted sum of national impacts but if $\eta > 0$, the impact of climate change on poor countries (relative to the world average) receive a greater weight than impacts on rich countries.

At the same time, curvature in the utility function can be viewed as a reflection of risk aversion. In this role, η explains why risk-averse people buy insurance; they are willing to pay a premium that is proportional in first order approximation to the parameter η to eliminate variability in outcomes because doing so increases their expected utility[7]. Note that η also affects the value one attaches to the impacts of climate change, but we abstract from this in our discussion.

3. Estimating the social cost of carbon

Armed with these insights from the first principles of microeconomic theory, we used the integrated assessment

[6] Strictly, ρ ranges between 0 and 3 per cent per year, while η, as a ratio of percentage changes, is unitless.

[7] The risk premium is, by definition, the difference between the expected outcome of a risky situation and the 'certainty equivalent' outcome—the guaranteed outcome that would sustain a level of utility equal to expected utility across the full range of possible outcomes. For a risk-averse individual, the certainty equivalent is always less than the mean because losses relative to the mean reduce utility more than equal gains above the mean.

model *FUND* to test the hypothesis that η could actually turn out to be more important in determining the SCC than ρ. In many ways, *FUND* is a standard integrated assessment model [9, 21, 22, 27]. It has simple representations of the demography, economy, energy, emissions, and emission reduction policies for 16 regions. It has simple representations of the cycles of greenhouse gases, radiative forcing, climate, and sea level rise. In other ways, though, *FUND* is unique. It is alone in the detail of its representation of the impacts of climate change. Impacts on agriculture, forestry, water use, energy use, the coastal zone, hurricanes, ecosystems, and health are all modelled separately—both in 'physical' units and their monetary value [23, 24]. Moreover, *FUND* allows vulnerability to climate change impacts to be an explicit function of the level and rate of regional development [25, 28]. See the SOM for more details on the model.

We estimated the SCC cost of carbon by computing the total, monetized impact of climate change along a business as usual path and along a path with slightly higher emissions between 2005 and 2014.[8] Differences in impacts were calculated, discounted back to the current year, and normalized by the difference in emissions[9]. The SCC is thereby expressed in dollars per tonne of carbon at a point in time—the standard measure of how much future damage would be avoided if today's emissions were reduced by one tonne. More details on *FUND* are provided in the SOM[10].

We estimated the SCC for a range of values for ρ and η, but we report our results in stages to highlight the triple role of η. We first consider results for cases in which η affected only the discount rate. That is, we pretended that uncertainty about climate change had been resolved and that income differences between countries were irrelevant. The second set of results put uncertainty back into the problem; the reported expected values of the SCC are the product of a Monte Carlo analysis of all the uncertain parameters in the *FUND* model. A third batch of results were drawn from the original world of perfect climate certainty, but social cost estimates applied equity weighting to the regional impacts of climate change. Finally, we report expected social cost estimates for cases in which both uncertainty and equity weighing play a role—the cases where η plays its theoretically appropriate triple role[11].

Based on first principles, we expected that the SCC would react as follows to parameter changes. The higher the pure rate of time preference, ρ, the less one cares about the future. Damages from climate change, as they occur over time, are therefore less of problem and the SCC should fall. Similarly, the higher risk aversion, η, the higher the discount rate in a scenario of growing per capita income and so the SCC should again fall. However, higher aversion to risk means that one is more concerned about uncertainty and particularly concerned about negative surprises; as a result, the SCC should rise with higher values of η. Furthermore, the higher aversion to risk also corresponds to greater concern about income distribution; if one assumes that climate change disproportionally affects the poor, then the SCC should again rise. Based on first principles, therefore, we can predict the effect of changes in time preference ρ, but the effect of risk aversion η is ambiguous.

4. Results

Figure 1 shows the SCC cost of carbon for the four cases, varying both ρ and η while figure 2 portrays various cross-sections. If we ignore concerns about equity and uncertainty (panel A), the SCC roughly decreases with the discount rate. For $\rho = \eta = 0$, SCC = \$1939/tC; it falls to SCC = \$10/tC for $\rho = \eta = 1$ and to SCC = $-$\$5/tC for $\rho = \eta = 2$. The sign changes because climate change is initially beneficial to the world economy. For $\rho = \eta = 3$, however, SCC climbs back to $-$\$4/tC because the discount rate is so high that it even discounts initial benefits significantly.

The profiles change when uncertainty is taken into account. Panel B shows that a maximum is still observed where $\rho = \eta = 0$ and the expected social cost of carbon, denoted E(SCC) equals \$2036/tC. This is a local maximum, though. E(SCC) falls monotonically as ρ increases. E(SCC) also falls initially as η (and thus the discount rate) increases, but it starts rising as a greater η values puts more emphasis on the tail of the distribution. For $\rho = 0$ and $\eta = 3$, E(SCC) = \$152 155/tC. E(SCC) is negative only for $\rho \geqslant 2.7\%$ and $1.10 \leqslant \eta \leqslant 2.25$.

Panel C shows that the results are different again with equity weighing [2, 8] and no uncertainty. For $\rho = \eta = 0$, SCC = \$1,939/tC; since $\eta = 0$ implies equal weights, this is the global maximum. A local maximum appears at SCC = \$122/tC when $\rho = 0$ and $\eta = 3$. Since this maximum is smaller than the expected social cost reported above for the second set of values for $\rho = 0$, $\eta = 3$, we see that uncertainty is a bigger concern for climate policy than equity, at least in terms of an aggregate measure like the SCC. A global minimum is observed when $\rho = \eta = 3$ and SCC = $-$\$50/tC. It emerges because CO_2 fertilization brings short-term benefits even to poor countries that will be hurt by climate change in the longer term. For these parameters, long-term losses are heavily discounted and short-term benefits in developing countries are emphasized. See the supplementary online material (available at stacks.iop.org/ERL/4/024002) for the case without CO_2 fertilization.

Estimates of expected social cost are similar when equity weighting is added to the complication of uncertainty. Panel D has a local a maximum at $\rho = \eta = 0$ as before where E(SCC) = \$2036/tC, but the global maximum is E(SCC) = \$120 977/tC at $\rho = 0$, $\eta = 3$. E(SCC) is lowest for a high ρ and a medium η; E(SCC) = \$9/tC, for example, at $\rho = 3.0\%$, $\eta = 0.90$. Note that the E(SCC) is strictly positive for this, the theoretically correct scenario.

[8] The social cost of carbon of emissions in future or past periods is beyond the scope of this paper.

[9] We abstained from levelizing the incremental impacts within the period 2005–14 because the numerical effect of this correction is minimal while it is hard to explain.

[10] Full documentation of the *FUND* model, including the assumptions in the Monte Carlo analysis, is available at http://www.fund-model.org.

[11] Note that we assume that the scenarios of population, economy, energy and emissions are independent of ρ and η. Implicitly, we thus assume that changes in ρ and η are exactly offset by changes in the scenario of technological change.

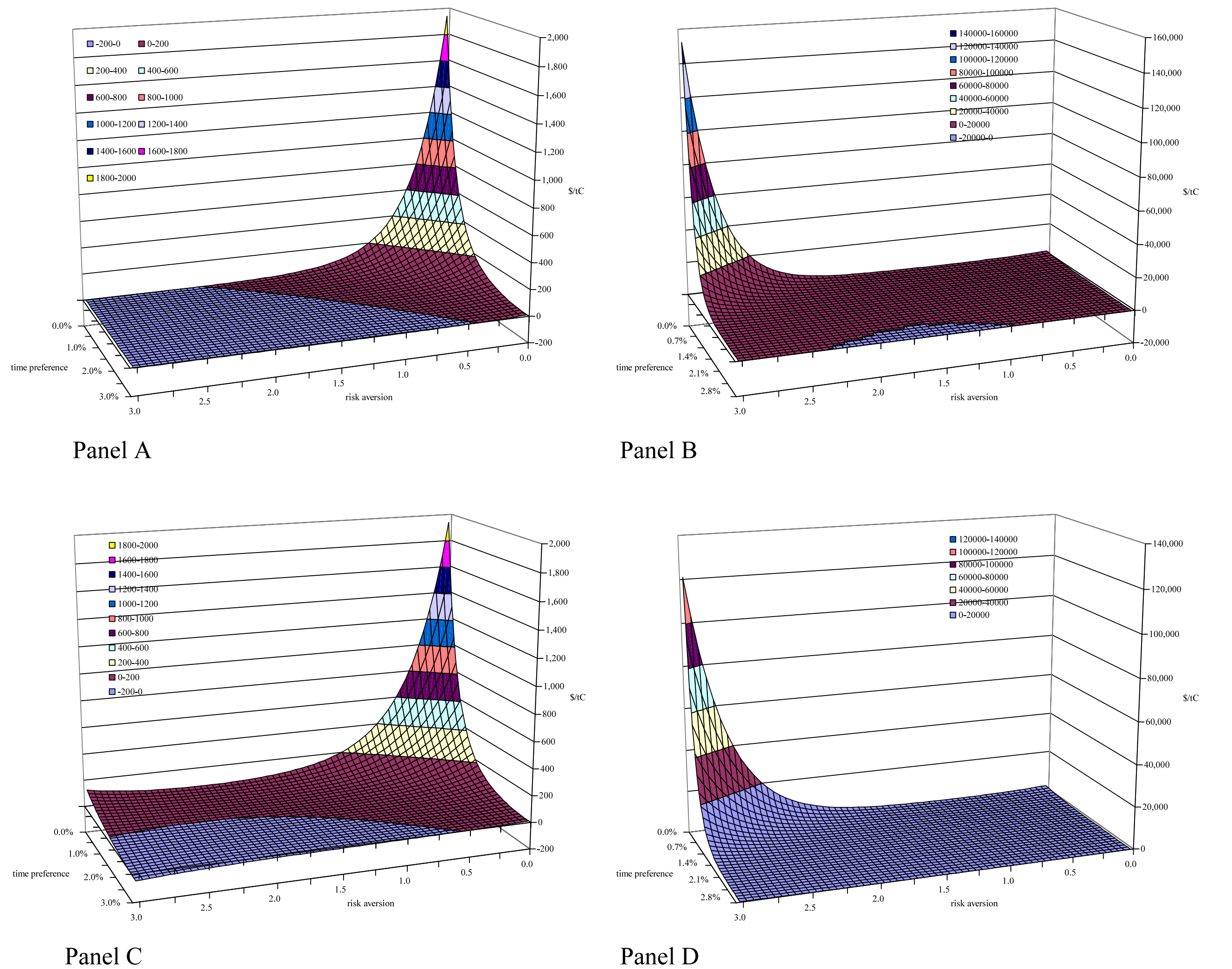


Figure 1. The marginal damage cost of carbon emissions as a function of the rate of time preference and the rate of risk aversion. Panel A (top left) shows the sensitivity of SCC estimates without equity weighting and without uncertainty; low pure rates of time preference and risk aversion produce high SCC estimates because they work exclusively through the discount rate. Panel B (top right) shows the sensitivity of SCC estimates to uncertainty without equity weighting; low rates of time preference produce higher estimates, but uncertainty dominates especially for high levels of risk aversion where the associated risk-premium climbs enormously. Panel C (bottom left) shows the sensitivity of SCC estimates to equity weighting derived from the 'inequity aversion' interpretation of η and without uncertainty; higher aversions to inequity reduce the SCC for any time preference because the positive gains in developing countries from CO_2 fertilization dominate 'downstream' losses that are, by virtue of the higher values for η, discounted more severely. Panel D (bottom right) shows the sensitivity of SCC estimates to equity weighting with uncertainty fully represented; the moderating effect of higher values for η is dominated by the effect of uncertainty.

For reference, Lord Stern of Brentford chose $\rho = 0.1\%$, $\eta = 1$; in our calibration through *FUND*, the result was E(SCC) = \$721/tC. Since the *Stern Review* essentially ignored equity weighing, though, E(SCC) = \$333/tC is a more comparable statistic. The *Stern Review* estimate E(SCC) = \$314/tC, which is remarkable close. However, note that the *Review* used the PAGE [10] model—which truncates the tails of distributions of input parameters that *FUND* fully recognizes[12], but keeps vulnerability to climate change as in 1995 while *FUND* has vulnerability declining with development—the two main differences between the two models roughly offset one another.

[12] Note that we discard the top and bottom 1% of Monte Carlo results because these outliers have an undue impact on the mean.

5. Choosing a social cost of carbon

We used two different approaches to inform our representations of combinations ρ and η that reflect actual practice across decision makers. In the first, we worked with results from Evans and Sezer [6, 7], who estimated $\eta = 1.49$, with a standard deviation of 0.19 for 22 rich and democratic countries from income redistribution data [17]. They also independently estimated $\rho = 1.08 \pm 0.20\%/\text{year}$ using data on mortality rates. Assuming normality, these results support the probability density function on ρ and η displayed in Panel A of figure 3. The first row of table 1 records estimates of the expected value of the SCC derived from this distribution for the four cases described above (see supplementary online material for

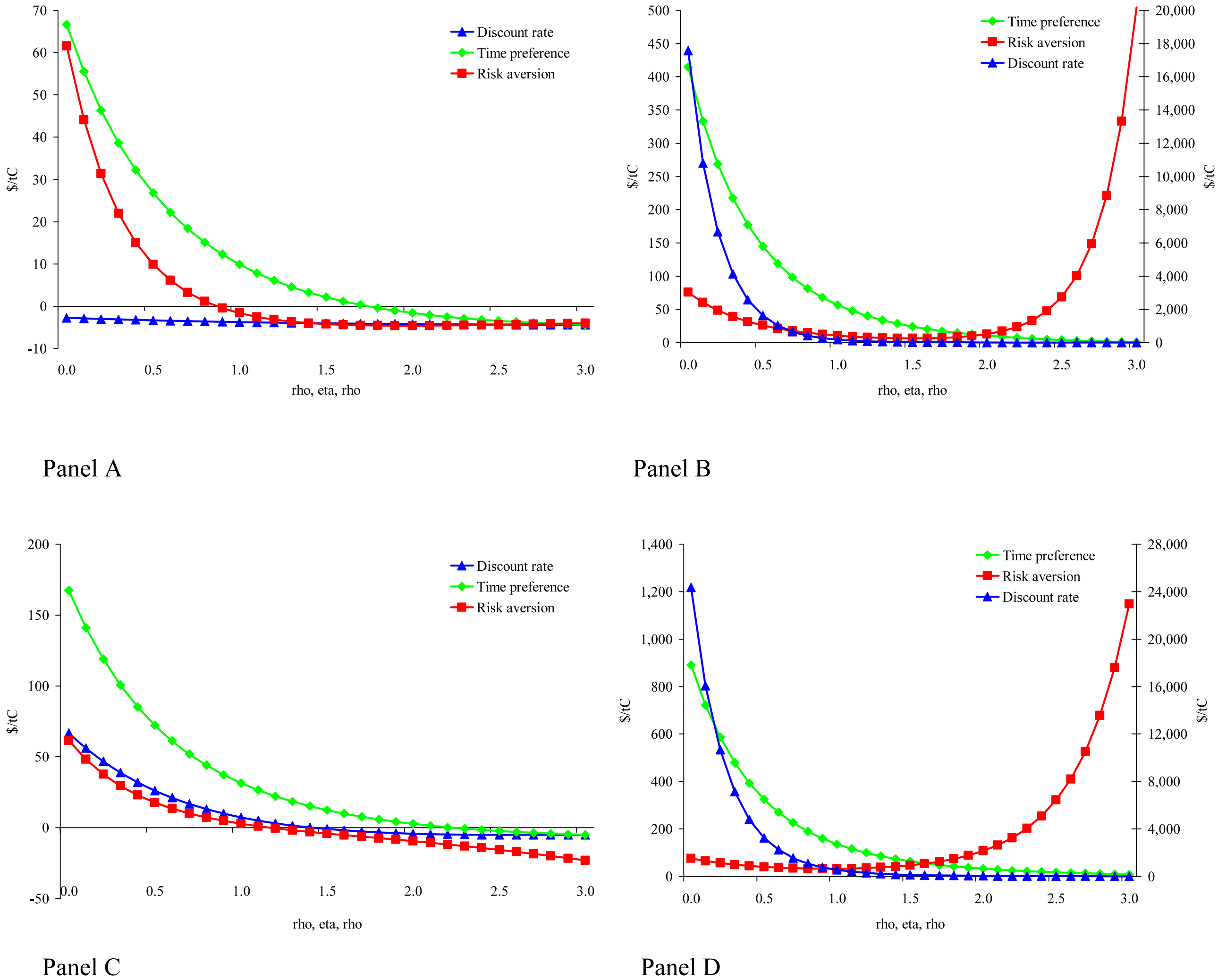
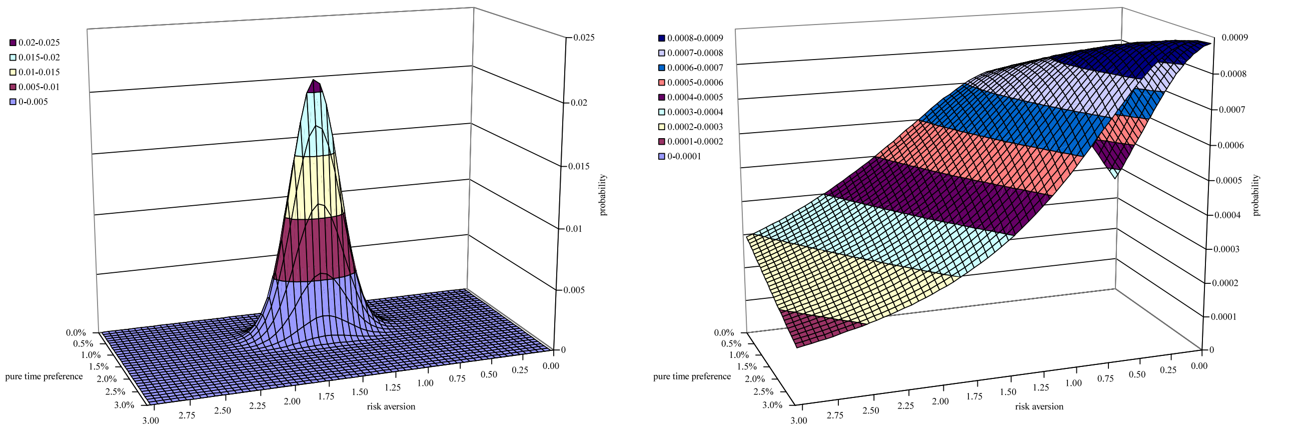


Figure 2. The SCC as a function of the rate of time preference (green diamonds for a rate of risk aversion of 1.0), the rate of risk aversion (red squares for a rate of time preference of 2.0), and of the rate to time preference (blue triangles for a rate of risk aversion adjusted to maintain the discount rate at 5.0 assuming that consumption grows at 2.0% per year—right axis). Panel A (top left) shows contours without equity weighting and without uncertainty. Negative values for SCC are possible for high rates of risk aversion and/or time preference (and guaranteed for a 5% discount rate); this is an indication of the conservative damage estimates embodied in *FUND*. Panel B (top right) displays contours with η working as a risk aversion parameter given complete manifestation of uncertainty but ignoring its role as equity weighting parameter at any point in time; the U-shaped contour associated with risk aversion is particularly instructive—the discounting effect of high values is dominated by the risk-premium effect of increased aversion to risk. Panel C (bottom left) shows contours with η working to produce equity weights without uncertainty; the early agricultural benefits of CO_2 fertilization in developing countries produces negative estimates for SCC for high discount rates born of high rates of risk aversion and/or time preference. Panel D (bottom right) allows η to work both as a source of equity weighting and as a measure of risk aversion given climate and socio-economic uncertainty; the U-shaped contours of the uncertainty only case from Panel B return.

details (available at stacks.iop.org/ERL/4/024002)). Ignoring concerns about equity and uncertainty, E(SCC) $= -\$1/\text{tC}$. Considering either equity or uncertainty alone increases the estimate to \$13/tC or \$62/tC, respectively. Uncertainty is again seen to play a larger role in determining the social cost of carbon than equity. Considering both equity and uncertainty produces the fourth estimate: E(SCC) $= \$210/\text{tC}$. Equity and uncertainty reinforce one another.

Our second approach relied data on per capita consumption growth rates, inflation rates, and nominal interest rates for 27 OECD countries from 1970 to 2006. We interpreted observations of the real interest rate (r in equation (1) and the difference between the nominal rate and the rate of inflation) and the growth rate g as drawings from a bi-variate normal distribution. The Ramsey equation implies that realizations for r and g together support a linear combination for ρ and η. As a result, the bi-variate distribution for r and g implies a degenerate bi-variate distribution for ρ and η. Panel B of figure 3 displays this distribution. The mean for η is 1.18, with a standard deviation of 0.80, but the distribution is right skewed with a mode of $\eta = 0.55$. The mean of ρ is 1.4%, with a standard deviation of 0.9%; the distribution is again right skewed, this time with a mode of $\rho = 0.9\%$. The characteristics of this distribution are not inconsistent with the underlying distributions reported by Evans and Sezer, but it does clearly differ in shape. The second row of table 1 shows



Panel A Panel B

Figure 3. Probability density functions of risk aversion and time preference. Panel A displays the distribution reported by Evans and Sezer. Panel B was derived from the Ramsey rule using OECD data.

Table 1. Estimates of the expected social cost of carbon ($/tC).

Uncertainty included?	No	No	Yes	Yes
Equity weighting included?	No	Yes	Yes	No
Rate of pure time preference and rate of risk aversion from Evans and Sezer	−0.7	12.6	210.1	61.6
Inference from interest rate and consumption growth rates from OECD countries	40.6	58.7	227.8	117.4
Both	−0.4	13.2	205.5	60.7

the sensitivity of E(SCC) estimates to the difference. Ignoring uncertainty and equity, E(SCC) = $41/tC; it is much higher than the estimate reported in the first row from the Evans and Sezer distribution because lower values of ρ and η are deemed more likely. As before, considering either equity or uncertainty increases the E(SCC), this time to $59/tC and $117/tC, respectively. The effects of equity and uncertainty are now less pronounced because extreme values of ρ and η receive lower probability mass than before. Finally, as before, uncertainty dominates equity. However, in this case, equity moderates uncertainty; considering both simultaneously produces an estimate for E(SCC) of $228/tC. Again, equity and uncertainty reinforce one another.

The third row of table 1 shows E(SCC) estimates for a combined probability density function of ρ and η produced by multiplying the two PDFs in figure 3 and rescaling them to integrate to unity. The estimates lie in between the previous results, but closer to the initial results derived from the Evans and Sezer PDF. The qualitative pattern is the same, though. Uncertainty dominates, and is reinforced by equity. Combining all of this information, our final estimate is E(SCC) = $206/tC.

6. Conclusion

Lord Stern [18] has expressed a preference for debating philosophically about the appropriate discount rate for the benefits of mitigation. We bow out of that debate by exploring the ramifications of actual decision makers and actual developed economies. We find that aversion to risk aversion is as important in determining SCC estimates as time preference. More specifically, we offer high estimates for the SCC given operational combinations of risk aversion and time preference even with a model that incorporates relative conservative damage estimates (including benefits early) and autonomous adaptation drive by regional economic development.

References

[1] Arrow K J 2007 Global climate change: a challenge to policy *Econ. Voice* **4** (3) 2
[2] Azar C and Sterner T 1996 Discounting and distributional considerations in the context of global warming *Ecol. Econ.* **19** 169–84
[3] Beckerman W and Hepburn C J 2007 Ethics of the discount rate in the Stern Review on the economics of climate change *World Econ.* **8** 187–208
[4] Broome J 1992 *Counting the Cost of Global Warming* (Cambridge: White Horse)
[5] Dasgupta P 2007 Commentary: the Stern Review's economics of climate change *Natl Inst. Econ. Rev.* **199** 4–7
[6] Evans D J and Sezer H 2004 Social discount rates for six major countries *Appl. Econ. Lett.* **11** 557–60
[7] Evans D J and Sezer H 2005 Social discount rates for member countries of the European Union *J. Econ. Stud.* **32** 47–59
[8] Fankhauser S, Tol R S J and Pearce D W 1997 The aggregation of climate change damages: a welfare theoretic approach *Environ. Resour. Econ.* **10** 249–66
[9] Guo J, Hepburn C J, Tol R S J and Anthoff D 2006 Discounting and the social cost of climate change: a closer look at uncertainty *Environ. Sci. Policy* **9** 205–16
[10] Hope C W 2008 Discount rates, equity weights and the social cost of carbon *Energy Econ.* **30** 1011–9
[11] Jensen P H and Webster E 2007 Is Stern correct? does climate change require policy intervention? *Aust. Econ. Rev.* **40** 421–31
[12] Lumer C 2002 *The Greenhouse—A Welfare Assessment and Some Morals* (Lanham: University Press of America)
[13] Mendelsohn R O 2008 Is the Stern Review an economic analysis? *Rev. Environ. Econ. Policy* **2** 45
[14] Nordhaus W D 2007 Critical assumptions in the Stern Review on climate change *Science* **317** 201–2
[15] Ott K 2003 Reflections on discounting: some philosophical remarks *Int. J. Sustain. Dev.* **6** 7–24

[16] Ramsey F 1928 A mathematical theory of saving *Econ. J.* **38** 543–9
[17] Stern N H 1977 Welfare weights and the elasticity of the marginal valuation of income *Studies in Modern Economic Analysis: Proc. Annual Conf. of the Association of University Teachers of Economics* ed M J Artis and A R Norbay (Oxford: Blackwell) pp 209–57
[18] Stern N H 2008 The economics of climate change *Am. Econ. Rev.* **98** 1–37
[19] Stern N H *et al* 2006 *Stern Review: The Economics of Climate Change* (Cambridge: Cambridge University Press)
[20] Stern N H and Taylor C 2007 Climate change: risks, ethics and the Stern Review *Science* **317** 203–4
[21] Tol R S J 1997 On the optimal control of carbon dioxide emissions: an application of *FUND Environ. Model. Assess.* **2** 151–63
[22] Tol R S J 1999 The marginal costs of greenhouse gas emissions *Energy J.* **20** 61–81
[23] Tol R S J 2002 Estimates of the damage costs of climate change. Part 1: benchmark estimates *Environ. Resour. Econ.* **21** 47–73
[24] Tol R S J 2002 Estimates of the damage costs of climate change. Part II: dynamic estimates *Environ. Resour. Econ.* **21** 135–60
[25] Tol R S J 2005 Emission abatement versus development as strategies to reduce vulnerability to climate change: an application of FUND *Environ. Dev. Econ.* **10** 615–29
[26] Tol R S J 2005 The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties *Energy Policy* **33** 2064–74
[27] Tol R S J 2006 Multi-gas emission reduction for climate change policy: an application of FUND *Energy J.* 235–50 (Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue)
[28] Tol R S J, Ebi K L and Yohe G W 2007 Infectious disease, development, and climate change: a scenario analysis *Environ. Dev. Econ.* **12** 687–706
[29] Weitzman M L 2007 A review of the Stern Review on the economics of climate change *J. Econ. Lit.* **45** 703–24
[30] Weyant J P 2008 A critique of the Stern Review's mitigation cost analyses and integrated assessment *Rev. Environ. Econ. Policy* **2** 77–93